ANSI C63.5-1998
(Revision of
ANSI C63.5-1988)

American National Standard for Electromagnetic Compatibility— Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz)

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Accredited Standards Committee on Electromagnetic Compatibility, C63

accredited by the

American National Standards Institute

Secretariat

Institute of Electrical and Electronics Engineers, Inc.

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American National Standards Institute

Abstract: Methods for determining antenna factors of antennas used for radiated emission measurements of electromagnetic interference (EMI) from 9 kHz to 40 GHz are provided. Antennas included are linearly polarized antennas such as loops, rods (monopoles), tuned dipoles, biconical dipoles, log-periodic dipole arrays, broadband horns, etc., which are used in measurements governed by ANSI C63.4-1992. The methods include standard site (i.e., 3-antenna), reference antenna, equivalent capacitance substitution, standard transmitting loop, standard antenna, and standard field methods.
Keywords: antenna factors, equivalent capacitance substitution, linearly polarized antennas, near free space, reference antenna, standard antenna, standard site, standard transmitting loop

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Introduction

[This introduction is not part of ANSI C63.5-1998, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz)].

ANSI C63.4-1992, American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronics Equipment in the Range of 9 kHz to 40 GHz, has undergone several revisions since the original document covering methods of measurement was produced in 1940. Although many improvements were made in the standard from time to time, the reproducibility of measurements of radiated interference from one test site to another has not been completely satisfactory.

In 1982 a concerted effort was organized in Subcommittee One of the Accredited Standards Committee C63 to determine how the technique could be improved. Evidence showed that the variability was due, in part, to inadequate (a) control of site ground plane conductivity, flatness, site enclosures, effects of surrounding objects, and certain other site construction features, (b) accounting for antenna factors, associated cabling, and balun and device under test characteristics, and (c) consideration of mutual coupling effects between the device under test and the receiving antenna and their images in the ground plane. Accordingly, ANSI C63.4 has been revised, and ANSI standards C63.5, C63.6, and C63.7 were prepared to provide additional information. This standard provides methods of calibration of antennas for use on the test site.

In 1993 a concerted effort was begun to bring the Standard Site Method of ANSI C63.5 into CISPR as the method of antenna calibration to be used in CISPR Publication 16. During the ensuing discussions, it became apparent that several features of ANSI C63.5 were not acceptable to the international community. In particular, calibration measurements at 3 m were unacceptable. Furthermore, while ANSI C63.5 recommends that only horizontal polarization be used for antenna calibration, it included information on calibration using vertical polarization. This was considered ambiguous and unacceptable by CISPR Subcommittee A. During the use of ANSI C63.5 over the last several years a number of errors were discovered and these needed to be corrected. ANSI standards C63.2 and C63.4 specify antennas from 9 kHz to 30 MHz and from 1000 MHz to 40 GHz for which no calibration procedure was available in ANSI C63.5. Accordingly, ANSI C63.5 has been revised to eliminate those features that the international community found objectionable, and thus provides harmonization with international standards while allowing a US National deviation from those standards. This revision corrects errors which use of the standard has shown, and extends it to cover all of the antennas specified in ANSI standards C63.2 and C63.4 from 9 kHz to 40 GHz.

Participants

At the time that the Accredited Standards Committee on Electromagnetic Compatibility, C63, approved this standard, it had the following membership:

Ralph M. Showers, *Chair* **Edwin L. Bronaugh,** *Vice Chair*

Patricia Gerdon, *Secretariat*

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American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz)

1. Scope

This standard provides methods for determining antenna factors of antennas used for radiated emission measurements of electromagnetic interference (EMI) from 9 kHz to 40 GHz. Antennas included are linearly polarized antennas, such as loops, rods (monopoles), tuned dipoles, biconical dipoles, log-periodic dipole arrays, broadband horns, etc., that are used in measurements governed by ANSI C63.4-1992. The methods include standard site, reference antenna, equivalent capacitance substitution, standard transmitting loop, standard antenna, and standard field methods. The latter three methods are incorporated by reference in 4.4.

Harmonization of this standard with international standards is achieved by providing two sets of measurement geometries in the 30 MHz to 1000 MHz frequency range. One set of one measurement geometry is provided for calibrations to meet international requirements, and one set of four measurement geometries is provided for calibrations to meet US domestic requirements. The international measurement geometry and one of the four domestic measurement geometries are identical. The international geometry is the preferred calibration measurement geometry.

2. References

The following references shall form a part of this standard to the extent referenced. When the standards referred to in this standard are superseded by a revision, the revision shall apply.

ANSI C63.2-1996, American National Standard for Electromagnetic Noise and Field-Strength Instrumentation, 10 kHz to 40 GHz—Specifications.[1]

[1]ANSI C63 publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331 USA.

ANSI C63.4-1992, American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz.[2]

ANSI C63.6-1996, American National Standard Guide for the Computation of Errors in Open-Area Test Site Measurements.

ANSI C63.7-1992, American National Standard Guide for Construction of Open-Area Test Sites for Performing Radiated Emission Measurements.

ANSI C63.14-1998, American National Standard Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatic Discharge (ESD).

ANSI/NCSL Z540-1-1994, American National Standard for Calibration—Calibration Laboratories and Measuring and Test Equipment–General Requirements.[3] (DoD has withdrawn MIL-STD-45662A and directed the use of ANSI/NCSL Z540-1-1994 instead.)

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.[4]

IEEE Std 149-1979 (Reaff 1990), IEEE Standard Test Procedures for Antennas.

IEEE Std 291-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.

3. Definitions

The following definitions apply specifically to the subject treated in this standard. For additional definitions, see ANSI C63.14-1992 and IEEE Std 100-1996.

3.1 ambient level. The values of radiated and conducted signal and noise existing at a specific test location and time when the test sample is not activated.

3.2 antenna factor. Quantity relating the strength of the field in which the antenna is immersed to the output voltage across the load connected to the antenna. (Antenna factor is independent of measurement geometry. Antenna is aligned with field polarization.)

3.3 free-space antenna factor. Antenna factor when all influences from adjacent objects have been removed.[5]

3.4 ground plane. A conducting surface or plate used as a common reference point for circuit returns and electric or signal potentials.

3.5 ideal site. A test site on which the reflective surface is flat and has infinite conductivity and size.

3.6 normalized site attenuation (NSA). Site attenuation divided by the antenna factors of the radiating and receiving antennas (all in linear units).

[2]Compliant with Part 15 of the FCC Rules and Regulations.

[3]NCSL standards are available from National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301 USA.

[4]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331 USA.

[5]"The magnitude of the ratio of the field strength of an incident co-polarized plane wave to the voltage developed across a specified impedance terminating the antenna output port, when the antenna is located in free space." (See Goedbloed [B7].)

3.7 radiated emissions test site. A site meeting specified requirements suitable for measuring radio interference fields radiated by a device, equipment, or system under test.

3.8 radio noise. An electromagnetic noise that may be superimposed upon a wanted signal and is within the radio-frequency range. For the purposes of this standard, an electromagnetic disturbance of a sinusoidal character is also considered radio noise.

3.9 random noise. Noise that comprises transient disturbances occurring at random.

NOTE—The part of the noise that is unpredictable except in a statistical sense. The term is most frequently applied to the limiting case where the number of transient disturbances per unit time is large, so that the spectral characteristics are the same as those of thermal noise (thermal noise and shot noise are special cases of random noise).

3.10 site attenuation. The ratio of the power input to a matched, balanced, lossless tuned dipole radiator to that at the output of a similarly matched, balanced, lossless tuned dipole receiving antenna for specified polarization, separation, and heights above a flat, reflecting surface.

3.11 standard antenna calibration site. A site comprised of a flat, open-area, devoid of nearby scatterers such as trees, power lines, and fences, that has a large metallic ground plane. The ground plane should be as large or larger than the first Fresnel ellipse and meet the Rayleigh criterion (see ANSI C63.7-1992). The clear area (sometimes referred to as the obstruction-free area) should be as large or larger than the third Fresnel ellipse (see ANSI C63.7-1992).

NOTE—A 10-meter test site that is weather-protected or installed in a suitable absorber-lined chamber may be used if it can be shown that the effects of the chamber or weather protection are insignificant.

4. General test conditions

This standard provides for "free-space" antenna factors that can be used for either vertically or horizontally polarized measurements at distances from the equipment under test (EUT) of 3 m or more. The general test conditions for antenna calibration are described in 4.1 through 4.4.

4.1 Measurement geometry

Accurate antenna calibration requires some restrictions on measurement geometry. The antenna separation distance R shall be great enough to ensure that near-field effects and antenna-to-antenna mutual coupling effects are minimized. Antenna heights (h_1, h_2) shall be great enough to minimize antenna-to-ground plane mutual impedance and to ensure negligible contribution from the surface wave component of the groundwave.

When tuned dipoles are calibrated using the methods in this standard, they shall be calibrated at separation distances R equal to or greater than 10 m and at heights equal to or greater than 2 m. The separation distance R between log-periodic array antennas is measured from the projection onto the ground plane of the midpoint of the longitudinal axis of each antenna.

4.2 Test instrumentation

Signal generators and power amplifiers shall have a 50 Ω output impedance. Radio noise meters, spectrum analyzers, other tuned voltmeters, and preamplifiers shall have a 50 Ω input impedance. Refer to ANSI C63.2-1996 for radio noise meter specifications.

An impedance mismatch at the output of signal sources or at the input of voltmeters may result in reflections that could cause antenna factor measurement errors. This should be avoided by the use of high-quality padding attenuators of 10 dB—one at the output end of the transmitting cable and one at the voltmeter input. The signal sources should provide sufficient power to produce a signal at least 10 dB above the ambient and equivalent receiver noise at the receiver input. Preamplifiers may be used at the voltmeter input to meet this requirement. The source power and preamplifier gain requirements shall depend upon voltmeter/preamplifier sensitivity, antenna factors, cable losses, and measurement distance. It is preferable to use preamplifiers at the voltmeter input rather than power amplifiers at the source output. This will improve the signal-plus-voltmeter-noise-to-voltmeter-noise ratio, while minimizing the potential for interference with susceptible equipment or licensed radio services in the vicinity of the test area.

Signal generators, antennas, and receiving equipment (voltmeters and preamplifiers) shall be calibrated at regular intervals. Calibration shall include amplitude uncertainty,[6] frequency uncertainty, drift, and sensitivity, where applicable. Effects of drift, especially during the measurement time, shall be compensated or corrected. These calibration standards shall be traceable to a national standard. An example of an acceptable program for calibration of instrumentation can be found in ANSI/NCSL Z540-1:1994.

4.3 Antenna factors

Individually measured antenna factors in the frequency range of 30 MHz to 1000 MHz, which are measured by these procedures, are capable of producing uncertainty values within ±1 dB from 30 MHz to 800 MHz, and within ±1.5 dB from 800 MHz to 1000 MHz. The user should verify that manufacturer-supplied antenna factors are based on individual calibrations of that specific antenna and that they are traceable to a national standard.

Antenna factors usually account for losses due to the balun. If a separate balun is used, its effects shall be measured or otherwise accounted for and included with the data to ensure that the user understands how any such separate balun is to be used and how its effects are to be accounted for. If the measured antenna factors are adjusted to correct for fixed-length cable losses, this shall be clearly stated in the antenna-factor data supplied to the user.

Experience has shown that variations of antenna factors with measurement geometry and polarization are negligible for electrically small antennas, provided that the antennas are well balanced. This includes the types of broadband antennas commonly used for EMI measurement from 30 MHz to 1000 MHz when used in the geometries recommended in ANSI C63.4-1992. Antenna factor variations may be caused by the use of unusual measurement geometries or mutual coupling, and measurement errors may be caused by poor balance and transmission line scattering for vertically polarized antennas. The antenna factors may be measured for a particular antenna as stated in 4.1. For this procedure, antenna height and pattern variation of less than ±1 dB are considered acceptable, and the measured antenna factors are considered independent of those two parameters; hence, they are considered "near free space" antenna factors.

Although not part of the antenna calibration procedure, it is prudent to check the balun balance of the antenna. To do this

a) Start by orienting the transmit and receive antennas horizontally with respect to the ground plane. Note the received signal in this position while keeping the transmit signal constant.

b) Rotate the receive antenna (the antenna being checked for balance) 90° into a vertically polarized position with respect to the ground plane. Note the received signal with the transmit signal continuing to be held constant. There should be a signal null in this position of at least 20 dB.

c) Next, rotate the receive antenna to 180°. Note the received signal. This signal level should be within 0.5 dB of that in the starting position, i.e., 0°.

[6]See [B8] and [B9] for definitions and discussions of uncertainty. Antenna factor measurement uncertainties are under consideration by IEC/CISPR.

d) Next, rotate the receive antenna to 270° into the vertical position. There should be another signal null in this position of at least 20 dB.

If the nulls are not found in the 90° and 270° positions or the received signals in the 0° and 180° positions differ by more than 0.5 dB, then the balance of the antenna is inadequate for making emission measurements. The balun should be repaired before proceeding with calibration and use of the antenna.

NOTE—During the entire procedure, it is important that the receive antenna feed cable be carefully arranged to keep the cable orientation from causing an apparent unbalanced condition.

4.4 Methods of antenna factor determination

Antenna factors can be accurately calibrated in several ways. The decision as to which approach is best in a particular case shall be based upon the time, instrumentation, and facilities available to the investigator.

Three methods are

— Standard Site Method (SSM)
— Reference Antenna Method (RAM)
— Equivalent Capacitance Substitution Method (ECSM)

These methods are described in Clauses 5, 6, and 7. The uncertainty of these methods depends on the quality of the measuring site for the SSM, the accuracy with which the reference antenna in constructed for the RAM, and the accuracy with which the monopole capacitance is simulated for the ECSM. The ECSM shall be used for calibration of rod (monopole) antennas from 9 kHz to 30 MHz for use in the measurements using monopole antennas in ANSI C63.4-1992.

Three additional methods are

— Standard Field Method (SFM) (IEEE Std 291-1991)
— Standard Antenna Method (SAM) (Fitzgerrel [B6],[7] Taggart and Workman [B14], IEEE Std 149-1979)
— Standard Transmitting Loop Method (STLM)—a specialized version of the Standard Antenna Method (IEEE Std 291-1991)

These methods are incorporated in this standard by these references. If disagreements arise, the SSM, ECSM and RAM shall take precedence over the SFM and SAM. The STLM shall be used for calibration of loop antennas from 9 kHz to 30 MHz for use in the measurements using loop antennas required by ANSI C63.4-1992.

5. Standard Site Method (30 MHz to 40 GHz)

5.1 General

The SSM for determining antenna factors (Smith [B12]) requires a standard antenna calibration site. This procedure provides free-space antenna factors that are used without further correction for emission measurements at specified polarizations, distances from the EUT, or heights above the ground plane.

NOTE—Horizontally polarized antennas shall be at least 1 m above the ground plane and the lower tips of vertically polarized antennas shall be at least 25 cm above the ground plane.

[7]The numbers in brackets preceded by the letter B correspond to those of the bibliography in Annex F.

Antenna factor calibration errors caused by site anomalies can only be detected by measurements on two independent sites or on two independent paths on large sites. For example, two independent 10 m paths can be readily accommodated on a 30 m test site.

NOTE—Antennas used to measure attenuation of an open-area test site should not have been calibrated on that same site because site imperfections may have affected the measured antenna factors. An exception may be made in the case of large open-area test sites. On these large sites, antennas may be calibrated on a propagation path, which is independent of the path used for EMI measurements.

The SSM (based solely on horizontal polarized measurements) provides antenna factor measurements from 30 MHz to 1000 MHz for both US domestic use and international use. The measurement method is the same in both cases, but the geometries are different. For domestic use, measurement distances are 3 m and 10 m, transmit antenna heights are 1 m and 2 m, and receive antenna search heights are from 1 m to 4 m. For international use, the measurement distance is 10 m, the transmit antenna height is 2 m, and the receive antenna search heights are from 1 m to 4 m. These dimensions are annotated in Table 1, which provides values for E_D^{max} for all geometries. (Figure 2 provides all measurement geometries.) The international calibration measurement geometry is the *preferred* measurement geometry.

Antenna factors shall only be determined for horizontal polarization on a standard antenna calibration site, hereafter referred to as a standard site, using the SSM. This measurement is relatively insensitive to site variations for horizontal polarization, and it yields free-space antenna factors even though the reflecting plane will not create a free-space environment during calibration. Horizontal polarization is preferred for antenna calibration because

a) Mutual coupling between the antenna and the orthogonal transmission line is negligible
b) Scattering from the transmission line is negligible
c) Calculations of the horizontal groundwave are simpler than calculations for the vertical groundwave
d) The surface wave component of the horizontal groundwave over earth is more tightly coupled to the surface
e) The horizontal groundwave is less sensitive to differences in surface conductivity and permittivity than the vertical wave
f) Ground screen edge reflections are smaller for horizontal polarization

Certain antennas, for example, electrically small antennas, biconical dipoles, broadband dipoles, log-periodic arrays designed for use above approximately 100 MHz, and horn antennas designed for use above 1 GHz, have antenna factors that are independent of height and polarization if they are at least 1 m above the ground plane. It is unnecessary to calibrate standard gain horn antennas for use above 1 GHz; rather, they are used as gain standards to calibrate other antennas (see 12.3.1 of IEEE Std 149-1979).

NOTE—Certain studies (Stecher [B13], Austin and Fourie [B1]) have shown a small height dependence in some wire-cage biconical antennas above about 200 MHz.

Table 1—Tabulations of E_D^{max} and 1 and 2-m source antenna heights (Including dipole and log-periodic array antennas above 1000 MHz)

Polarization	Horizontal[a]	Horizontal[b]	Horizontal[a]	Horizontal[c]
R meters	3	3	10	10
h_1 meters	1	2	1	2
h_2 meters	1 – 4	1 – 4	1 – 4	1 – 4
f_M MHz	E_D^{max} dB(μV/m)			
30	3.5	8.4	–10.4	-4.8
35	4.6	9.2	–9.1	-3.6
40	5.6	9.9	–8.0	-2.6
45	6.4	10.3	–7.0	-1.7
50	7.1	10.7	–6.1	-0.9
60	8.3	11.2	–4.7	0.2
70	9.2	11.4	–3.5	1.1
80	10.0	11.6	–2.4	1.7
90	10.5	11.6	–1.6	2.0
100	10.9	11.7	–0.8	2.2
120	11.6	11.7	0.4	2.4
140	11.9	11.8	1.2	2.5
160	12.2	11.5	1.8	2.6
180	12.4	11.0	2.1	2.6
200	12.5	11.3	2.3	2.6
250	12.6	11.6	2.5	2.7
300	12.1	11.7	2.6	2.7
400	11.7	11.8	2.7	2.7
500	12.2	11.7	2.8	2.6
600	12.2	11.7	2.8	2.6
700	12.6	11.7	2.8	2.7
800	12.1	11.7	2.8	2.7
900	12.3	11.7	2.6	2.7
1000	12.4	11.7	2.7	2.7
1500	12.5	—	—	—
2000	12.5	—	—	—
2500	12.6	—	—	—
3000	12.6	—	—	—
3500	12.6	—	—	—
4000	12.6	—	—	—
4500	12.6	—	—	—
5000	12.5	—	—	—

[a]For domestic (USA) use for broadband antennas.
[b]For domestic use for all antennas.
[c]For international use for all antennas, and domestic use for tuned dipoles.

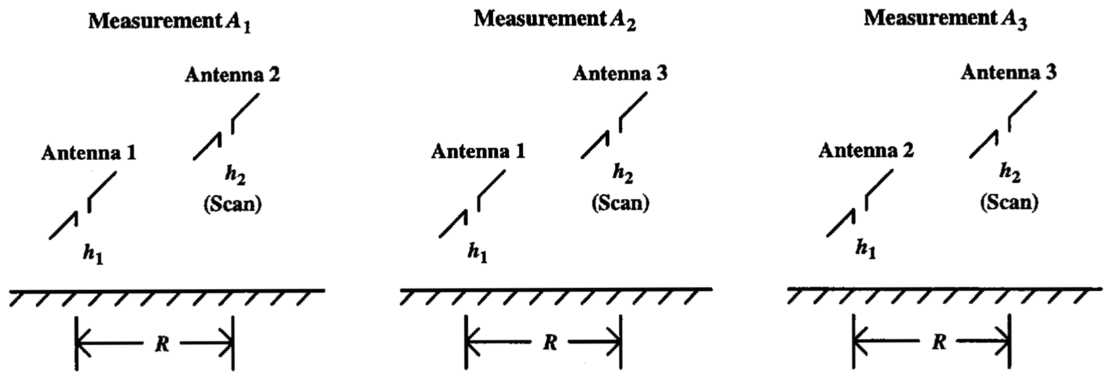


Figure 1—Three insertion loss measurements using three different antennas in pairs

5.2 Description of method

The SSM requires three insertion loss measurements under identical geometries (h_1, h_2, R) using three different antennas taken in pairs, as shown in Figure 1. The three equations associated with the three insertion loss measurements are Equations (1), (2), and (3).

$$AF_1 + AF_2 = A_1 + 20 \log f_M - 48.92 + E_D^{max} \quad (1)$$

$$AF_1 + AF_3 = A_2 + 20 \log f_M - 48.92 + E_D^{max} \quad (2)$$

$$AF_2 + AF_3 = A_3 + 20 \log f_M - 48.92 + E_D^{max} \quad (3)$$

(All equations in dB)

where

E_D^{max} is the maximum received field at separation distance R from the transmitting antenna, shown in Tables 1 and 2, in dB(μV/m). (See Smith [B12] and Annex A.)

AF_1, AF_2, AF_3 are the antenna factors of antennas 1, 2, and 3 in dB(1/m).

A_1, A_2, A_3 are the measured insertion losses in dB. (See Figure 1.)

f_M is the frequency in MHz.

Solving Equations (1), (2), and (3) simultaneously gives the desired expressions for the antenna factors in terms of the groundwave field strength term and measured insertion losses. They are as follows:

$$AF_1 = 10 \log f_M - 24.46 + 1/2\ [E_D^{max} + A_1 + A_2 - A_3] \quad (4)$$

$$AF_2 = 10 \log f_M - 24.46 + 1/2\ [E_D^{max} + A_1 + A_3 - A_2] \quad (5)$$

$$AF_3 = 10 \log f_M - 24.46 + 1/2\ [E_D^{max} + A_2 + A_3 - A_1] \quad (6)$$

If two identical antennas are to be calibrated, their antenna factor, AF [dB(1/m)], can be obtained from a single insertion loss measurement, A (dB), using the following expression:

$$AF = 10 \log f_M - 24.46 + 1/2 \, [E_D^{max} + A] \tag{7}$$

In practice, two antennas are never identical, and the antenna factor calculated by Equation (7) is the geometric mean of the individual factor for each of the two antennas. Certain antennas can be constructed to be so nearly identical that their factors are different by much less than the measurement uncertainty.[8]

If two antennas are to be calibrated and the antenna factors of one are known, use Equation (8).

$$AF_1 = A_1 + 20 \log f_M - 48.92 + E_D^{max} - AF_2 \tag{8}$$

where AF_2 is the known antenna factor.

NOTE—The uncertainty of antenna factors determined by the SSM from Equations (4), (5), (6), (7), and (8) depends on the uncertainty of the insertion loss measurement. Measurement uncertainty refers to the uncertainty of the instrumentation calibration and stability during the measurements, and how carefully the measurements are made.

Insertion loss measurement errors in Equations (4) through (7) can be minimized by judicious selection of the measurement method since insertion loss is just a measure of the ratio $V_{direct} : V_{site}$, where V_{direct} is the voltmeter input voltage when the signal generator and voltmeter are connected directly together through the transmission lines and attenuators, and V_{site} is the voltmeter input voltage when the signal generator is connected to the transmitting antenna and the voltmeter is connected to the receiving antenna. Recommended methods for discrete and swept frequency insertion loss measurements are identical to the methods for normalized site attenuation measurements given in ANSI C63.4-1992, except that antenna factors are not subtracted. The term *insertion loss* is used to clearly separate the antenna factor measurement procedures from a similar site attenuation measurement procedure described in ANSI C63.4-1992.

Scanning of the receiving antenna height h_2 is a practical requirement that eliminates the sensitivity of measurement to nulls. (The large spatial rate of change of the field in the region of a null can result in large measurement errors from small errors in antenna positioning.) Fixed receiving antenna heights may be used for geometries and frequencies where nulls are absent. Antenna separation of 10 m is recommended for antenna calibration measurements. Values of E_D^{max} for some typical geometries over metal ground planes are given in Table 1. (See also ANSI C63.4-1992.) See Smith [B12] for values over earth. Broadband horn antennas are calibrated using the same method with the exception that height search is not necessary in geometries in which the ground reflection point is not within the beams of the antennas. Horn antennas should be calibrated at a distance equal to or greater than $R = 2D^2/\lambda$; horn antennas shall not be calibrated at a distance less than $R = 0.5D^2/\lambda$. D is the largest linear dimension of the aperture of the antenna and λ is the wavelength at the frequency being considered, both in meters.

5.3 Measurement procedures

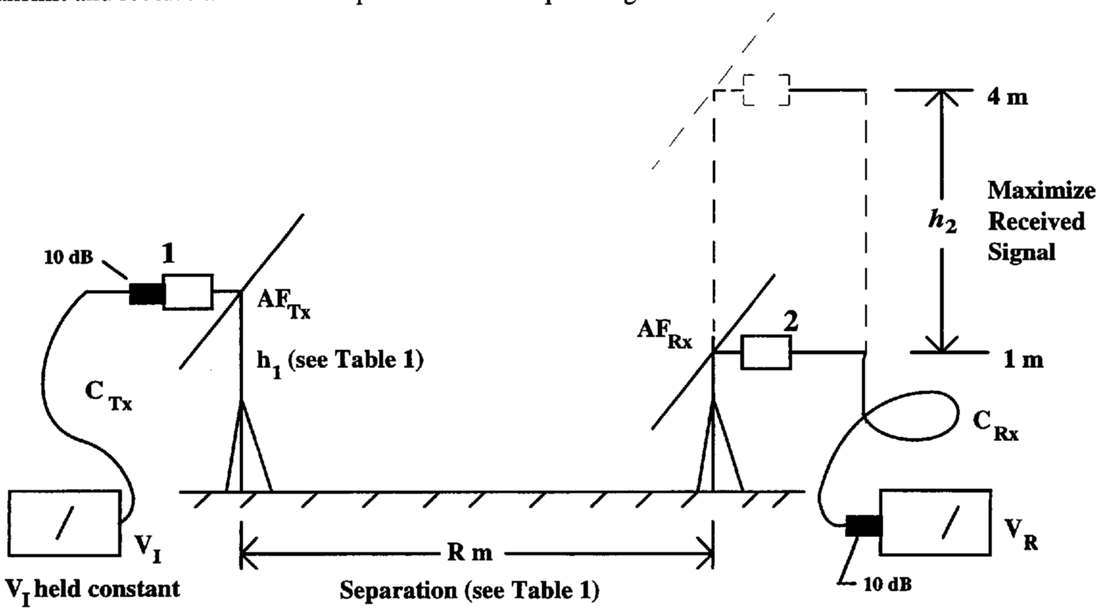
Two measurement procedures may be used to determine insertion loss—a *discrete frequency method* and a *swept frequency method*. The discrete frequency method requires a signal generator and radio noise meter or spectrum analyzer, and may be used with broadband or tunable antennas. The swept frequency method requires a tracking generator and automatic spectrum analyzer, or other automatic measuring equipment, and may be used only with broadband antennas.

NOTE—For both methods, an impedance mismatch at the output of the signal source or at the input of the radio noise meter or spectrum analyzer may result in reflections that could cause errors. This should be avoided by using high quality padding attenuators of 10 dB: one at the output end of each transmitting and receiving cable. These attenuators shall remain in the cables for both V_{direct} and V_{site} measurements. See ANSI C63.4-1992.

[8]See the decription of the reference antenna described in 6.2 of this standard.

5.3.1 Discrete frequency method

For the discrete frequency method, specific frequencies (given in Table 1) are measured in turn. At each frequency, the receive antenna is scanned over the height range given in the appropriate table to maximize the received signal. These measured parameter values are inserted in Equations (4), (5), and (6) to obtain the measured antenna factors. Refer to Figure 2 for the measurement geometry. For horn antennas, the frequency range in Table 2 is measured at the specific frequencies given in the note below the table. Both the transmit and receive antennas are operated at fixed equal heights of 2 m or more.



NOTE—Signal cables shall be dressed straight back from the antenna connector at least 1 m before being dressed vertically down to the ground plane. Signal cables that are dressed orthogonally to the antenna elements will have minimal coupling to the antenna field, but the cable shields may carry external currents caused by balun imperfections. Also, portions of the cables that are not straight down or straight back will couple to the antenna fields. See [B2] and [B3] for further discussion of these effects.

Figure 2—Insertion loss (horizontal polarization)

Table 2—Tabulations of E_D^{max} for horn antennas (no ground reflections)

R meters	3
h_1 meters	≥ 2[a]
h_2 meters	≥ 2[a]
f_M GHz	E_D^{max} dB(μV/m)
1.0 – 40.0	7.4

[a] $h_1 = h_2 \geq 2$ m

5.3.1.1 Procedure

1) Allow the signal generator and measuring instrument to warm up as specified by the manufacturer of the equipment. Call the signal at the generator output V_I, which is held constant throughout the measurement.
2) At the selected distance and frequency, which is entered in Figure B.1 (Annex B), connect the antennas (antennas 1 and 2) via cables to their respective signal source (transmitting antenna) and measurement instrument (spectrum analyzer or radio noise meter) and adjust the height of the receiving antenna for the maximum received signal. Adjust the substitution attenuator for reference indication on the measuring instrument. Record these data as V_{site} in Figure B.1.
3) Disconnect the cables to antennas and connect the cables directly together. Adjust the substitution attenuator to give the same reference indication as in step 2) and record the data as V_{direct} in Figure B.1.
4) Find the difference in attenuation by subtracting "attenuation for antenna-to-antenna mode" in step 2) from the "attenuation for direct connection mode" in step 3) in Figure B.1 and record this as A_1 in Figure B.3.
5) Change the frequency (see Table 1 or Table 2) and repeat steps 2) through 4).
6) After all frequencies are used, steps 2) through 4) are repeated twice, once for each of the remaining antenna pairings (antennas 1 and 3, antennas 2 and 3) to get the values for A_2 and A_3, respectively. Enter the results in Figure B.3.
7) Convenient worksheets for carrying out the necessary calculations are given in Annex B. Figure B.1 is a data recording and insertion loss calculation worksheet, Figure B.2 is an example of the use of Figure B.1, Figure B.3 is the antenna factor calculation worksheet, and Figure B.4 is an example of Figure B.3.

NOTE—The signal generator output attenuator may be used in place of an external substitution attenuator in the path between the generator and the transmit antenna.

The values of E_D^{max} listed in Table 1 were calculated for metal ground planes using K = 1, σ = (defined in Annex A). This table stops at 5 GHz because the type and length of cables becomes critical above 5 GHz. Also, height searching may not be practical above 5 GHz because of cable considerations.Calibrate horn antennas each 500 MHz from 1GHz through 12 GHz, each 1 GHz from 12 GHz through 18 GHz, and each 2 GHz from 18 GHz through 40 GHz.

5.3.2 Swept frequency method

For the swept frequency method, measurements using broadband antennas may be made using automatic measuring equipment having a peak hold (maximum hold), storage capability, and a tracking generator. In this method, both antenna height and frequency are scanned or swept over the required ranges, except for horn antennas, which are used at a fixed height of 2 m.

NOTES
1— The automatic measuring equipment may be computer controlled provided the software produces the same results as non-automated measurements.
2— Transient events may add significant error to the data; therefore, care should be taken to check for such effects.

5.3.2.1 Procedure

1) Allow the signal generator and measuring instrument to warm up and stabilize as specified by the manufacturer of the equipment. Call the signal at the generator output V_I, which is held constant throughout the measurement.
2) At the selected distance, connect the antennas (antennas 1 and 2) via cables to their respective signal source (transmitting antenna) and measurement instrument (receiving antenna). Raise the receiving antenna on the mast to the maximum height of the scan range or fixed height as indicated in the appropriate Table 1. Use fixed heights of 3 m for horn antennas in Table 2.

3) Set the instrument to sweep the desired frequency range. Ensure that the instrument is adjusted so that a similar signal up to 60 dB higher can be displayed on the same amplitude scale. This will accommodate the level to be recorded in step 5).
4) Slowly lower the receiving antenna to the minimum height of the scan range as indicated in Table 1 for the appropriate site geometry. Store or record the maximum received voltage display V_{site} in dB (μV). (The time it takes to lower the antenna should be much longer than the instrument sweep time.)
5) Disconnect the cables from the antennas and reconnect the transmit and receive cables with a straight-through adapter. Store or record the resulting voltage display V_{direct} in dB (μV).
6) At each frequency, subtract the voltage measured in step 4) from the voltage measured in step 5). The result is the measured insertion loss over the range of frequencies used, which should be stored.
7) Repeat steps 2) through 6) for each pair of antennas.

6. Reference Antenna Method (30 MHz to 1 GHz)

The Reference Antenna Method (RAM) provides a method of antenna calibration based on the use of a dipole with a well-matched balun whose construction is described in 6.2. This yields an antenna whose gain pattern and antenna factors are close to those predicted in theory

6.1 Calibration of other antennas using the reference dipole antenna

The antenna factor of any other antenna may be derived by substitution against the reference dipole antenna. The geometry shown in Figure 3 should be employed. The 10 m separation distance is employed to eliminate any significant antenna impedance variations caused by antenna-to-antenna mutual impedance coupling. Antenna A1 can be any type of antenna, including the reference antenna. Its purpose is to generate a field for measurement at A2. Set it at 2.5 m to 4 m above the ground[9] and drive it with a signal generator. To calibrate the unknown antenna against the reference dipole antenna, first measure signal strength with the reference antenna at A2. The antenna should be between 2.5 m and 4 m above the ground. It is not important to position the antenna to a signal maximum, but it is important to avoid the region around a null where readings will be changing rapidly with the antenna position. Find a position in the 2.5 m to 4 m range where signal amplitude is varying slowly with height. After the signal strength is noted with the reference dipole antenna, the antenna being calibrated should be substituted for the reference dipole, keeping the antenna to be calibrated at exactly the same height and position as was the reference dipole. (Scanning the receiving antennas in height while recording the maximum received voltages will facilitate the measurements, especially at higher frequencies where many peaks and nulls of the field are present.)

The ratio between the two measurements of the generated field strength is the difference (in dB) in the antenna factors between the reference antenna and the unknown antenna. If a lower signal is measured with the unknown antenna, the difference (in dB) should be added to the antenna factor of the reference antenna to obtain the antenna factor of the unknown antenna. If the signal measured with the unknown antenna is larger than that measured with the reference antenna, the difference should be subtracted from the antenna factor of the reference antenna to obtain the antenna factor or the unknown antenna. Recommended frequency intervals are 5 MHz below 50 MHz, 10 MHz between 50 MHz and 100 MHz, 25 MHz from 100 MHz to 200 MHz, 50 MHz from 200 MHz to 300 MHz, and 100 MHz from 300 MHz to 1000 MHz.

The length of each element of the reference antenna and its antenna factors are tabulated versus frequency in Table 3.

[9]A lower transmitting antenna height, for example, 0.75 m may be used above approximately 500 MHz in order to reduce the number of field strength peaks and nulls.

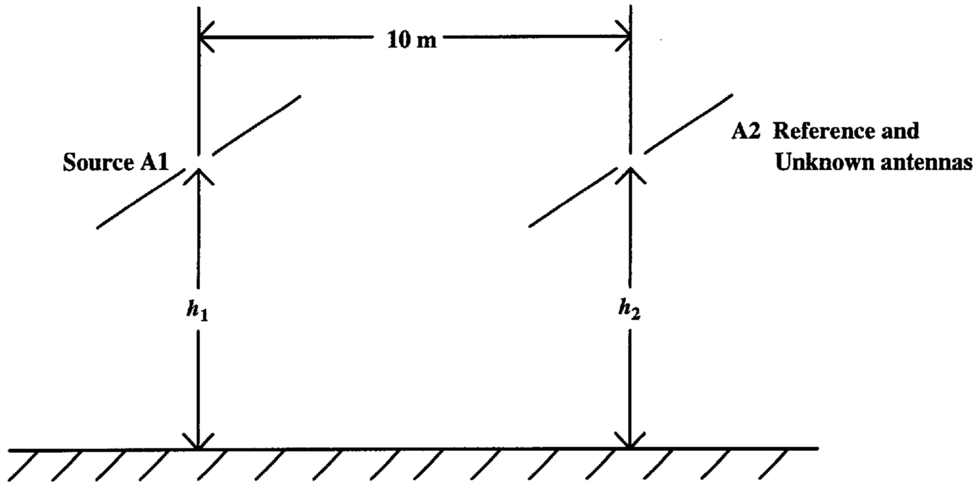


Figure 3—Geometry for calibrating antennas against the reference antenna

6.2 Description of the reference antenna

The reference antenna is a tuned, half-wavelength-resonant dipole with a series-parallel coaxial stub balun.

A four-antenna set can be used to cover the measurement range of 30 MHz to 1000 MHz. Physical construction details of the balun, antenna housings, and elements are shown in Figures E.1 through E.9. (See also FCC Project 3235-16 [B4]; FCC Project 3235-33 [B5]; Roberts [B10]; Roberts [B11].) The dimensions that are electrically critical are those that influence the balun series and parallel stub construction. These dimensions are shown in Figure E.1. The baluns should be constructed from a high quality RG-58/U cable such as Belden 8240.

After construction, a preliminary ohmic check should be performed. The resistance from the center conductors to the shield should be very large, that is, an open circuit. A preliminary back-to-back balun test shall also be performed before the baluns are installed in their housings by using the test setup of Figure E.10. The loss per balun in this test is one-half of the total loss measured and should be between 0.2 dB and 0.5 dB per balun over its frequency range.

A Voltage Standing Wave Ratio (VSWR) check will provide assurance of the performance of the assembled antennas. VSWR shall be measured with the antenna assembled and its elements tuned to resonance. The antenna shall be placed at least 4 m above the ground, higher if possible, to minimize antenna-to-ground coupling, and its elements tuned to resonance, using the measurements shown in Table 3. It is sufficient to check the VSWR of the antennas at frequencies in the low, middle, and high end of their frequency ranges. Below 100 MHz, the function of the baluns may also be checked by removing the elements, placing a 70 Ω resistor across the terminals of the element mounting block, and measuring the VSWR of the terminated balun.

NOTE—Make sure that the reactance of the 70 Ω resistor is much smaller than its resistance.

Antenna factors for the reference antenna are tabulated in Table 3 and were computed from Equation (9), the formula for the antenna factor of a lossless dipole. This shall be combined with an averaged loss for the matching balun of 0.5 dB (FCC Project 3235-16 [B4], FCC Project 3235-33 [B5]).

$$AF = 20 \log f_M - 31.4 \tag{9}$$

where f_M is in MHz.

Experimental data (FCC Project 3235-33 [B5]) have shown that the antenna-to-antenna variation to be expected due to construction tolerances is of the order of ±0.3 dB.

Table 3—Length of each element of the reference dipole antenna for resonant setting and antenna factor versus frequency

Frequency MHz	Length of each antenna element measured from center of antenna			*AF* dB(1/m)
	Metric[a]	English		
	(m)	(ft)	(in)	
30	2.413	7	11	-1.8
35	2.080	6	9-7/8	-0.5
40	1.803	5	11	0.6
45	1.600	5	3	1.7
50	1.438	4	8-5/8	2.6
60	1.197	3	11-1/8	4.2
70	1.026	3	4-3/8	5.5
80	0.889	2	11	6.7
90	0.791	2	7-1/8	7.7
100	0.714	2	4-1/8	8.6
120	0.589	1	11-1/8	10.2
140	0.500	1	7-5/8	11.5
160	0.438	1	5-1/4	12.7
180	0.389	1	3-1/4	13.7
200	0.352	1	1-7/8	14.6
250	0.283	—	11-7/8	16.6
300	0.235	—	9-1/4	18.1
400	0.175	—	6-7/8	20.6
500	0.143	—	5-5/8	22.6
600	0.117	—	4-5/8	24.2
700	0.102	—	4	25.5
800	0.089	—	3-1/2	26.7
900	0.079	—	3-1/8	27.7
1000	0.076	—	3	28.6

[a]Antenna designed in English units, but the values stated are computed metric values to nearest millimeter.

7. Equivalent Capacitance Substitution Method

The Equivalent Capacitance Substitution Method (ECSM) shall be used to calibrate rod (monopole) antennas from 9 kHz to 30 MHz. In this method, a dummy antenna consisting of a capacitor equal to the self-capacitance of the rod or monopole is used in place of the actual rod (see 2.4 of IEEE Std 291-1991). This dummy antenna is fed by a signal generator and the output from the coupler or base unit of the antenna is measured. For least uncertainty, the input voltage to the dummy antenna is also measured. The antenna factor in dB(1/m) is given by Equation (10). The test configurations are shown in Figure 4.

$$AF = V_D - V_L + 6.02 \tag{10}$$

where

V_D is the measured output of the signal generator in dB(μV)
V_L is the measured output of the coupler in dB(μV)

The factor 6.02 corrects for the effective height of the rod (see Annex D). For practical purposes use 6.0 dB in the Equation (10), above.

NOTE—The effective height of the 1.04 m rod is 0.5 m. The value of the dummy antenna (capacitor) used with Equation (9) is 10 pF. This value is correct for the 1.04 m (41 in) rod or monopole antennas usually used in EMC measurements. However, see Annex D to calculate the self-capacitance of rod antennas of unusual dimensions.

Two procedures may be used—one using a signal generator and a radio-noise meter, the other using a network analyzer. The same dummy antenna (equivalent capacitance) is used in both procedures. (See Annex D for guidance in making the dummy antenna.) The measurements shall be made at a sufficient number of frequencies to obtain a smooth curve of antenna factor vs. frequency over the operating frequency range of the antenna or 9 kHz to 30 MHz, whichever is smaller.

7.1 Radio-noise meter and signal generator procedure

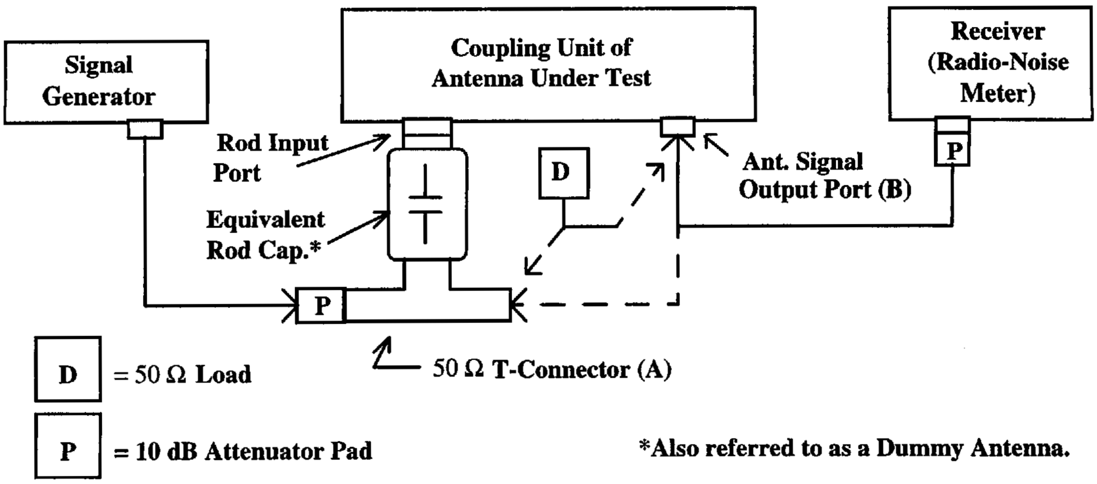
1) Set up the antenna to be calibrated and the test equipment as shown in Figure 4(a).
2) With the equipment connected as shown and a 50 Ω termination on the T-connector (A), measure the received signal voltage V_L in dB(μV) at the signal output port (B).
3) Leaving the RF output of the signal generator unchanged, transfer the 50 Ω termination to the signal output port (B) and transfer the receiver input cable to the T-connector (A). Measure the drive signal voltage V_D in dB(μV).
4) Subtract V_L from V_D and add 6 dB to obtain the antenna factor (in dB) of the antenna.

NOTE—The signal generator does not have to be calibrated, but it shall be stable. The 50 Ω termination shall have low VSWR. The radio-noise meter shall be calibrated and have low VSWR.

7.2 Network analyzer procedure

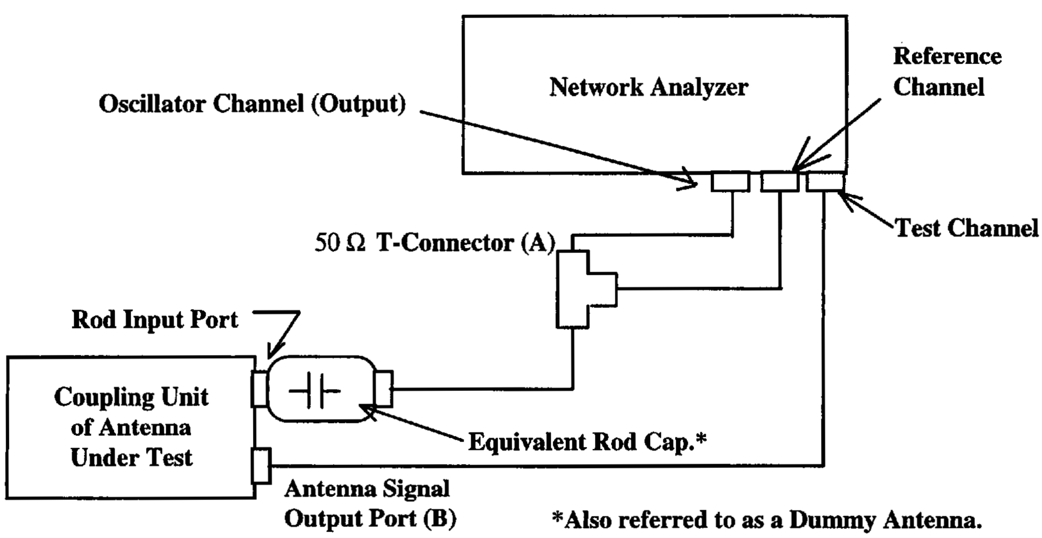
1) Calibrate the network analyzer with the cables to be used in the measurements.
2) Set up the antenna to be calibrated and the test equipment as shown in Figure 4(b).
3) Subtract the signal level (in dB) in the reference channel from the signal level (in dB) in the test channel and add 6 dB to obtain the antenna factor (in dB) of the antenna.

NOTE—Attenuator pads are not used with the network analyzer because the impedances of the channels in the network analyzer are very nearly 50 Ω and any errors are corrected during calibration. Attenuator pads may be used if desired, but including them complicates the network analyzer calibration.



NOTES
1—If VSWR of receiver or signal generator is low, pads may not be needed or may be reduced to 6 dB or 3 dB.
2—The T-connector may be built into the dummy antenna.
3—The dummy antenna may incorporate other matching components to control VSWR at its input and signal generator level measuring ports.

(a) Method using receiver (radio-noise meter) and signal generator



NOTES
1—Attenuator pads not used with network analyzer. Place T-connector as close to dummy antenna port as possible. Use same length and type of cables between T-connector and reference channel input and antenna signal output port and test channel.
2—The T-connector may be built into the dummy antenna.
3—The dummy antenna may incorporate other matching components to control VSWR at its reference channel and oscillator channel ports.

(b) Method using network analyzer

Figure 4—Measurement of rod (monopole) antenna factor

Annex A

(informative)

Maximum received field

For Table 1:

The following expressions for E_D^{max} are derived in Smith [B12]. Refer to Figure A.1 for the geometry.

For horizontal polarization, E_D^{max} is given by

$$E_{DH}^{max} = \frac{\sqrt{49.2}\{d_2^2 + d_1^2|\rho_h|^2 + 2d_1d_2|\rho_h|\cos[\phi_h - \beta(d_2 - d_1)]\}^{1/2}}{d_1d_2} \tag{A.1}$$

maximized over the interval $h_2^{min} \le h_2 \le h_2^{max}$,

where

$d_1 = [R^2 + (h_1 - h_2)^2]^{1/2}$

$d_2 = [R^2 + (h_1 - h_2)^2]^{1/2}$

$$\rho_h = \frac{\sin\gamma - (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}}{\sin\gamma + (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}} = |\rho_h|e^{j\phi_h}$$

K is the relative dielectric constant

σ is the conductivity, siemens per meter (S/m)

γ is the grazing angle (see Figure A.1)

ϕ is the phase angle of reflection coefficient

$\beta = 2\pi/\lambda$

λ is the wavelength, meters

Equation (A.1) is the maximum value over the receiving antenna height scan range h_2^{min}, h_2^{max} of the space wave fields radiated by a half-wave dipole antenna emitting one picowatt of radiated power. The transmitting dipole and the receiving antenna are spaced a distance R apart, and the transmitting dipole is at height h_1.

For Table 2:

For horn antennas where the ground reflection is non-existent or is not picked up by the antenna being calibrated, $\rho_h \to 0$ and

$$E_D^{max} = 10 \log 49.2 - 20 \log R = 16.9 - 20 \log R, \text{ dB}(\mu\text{V/m}) \tag{A.2}$$

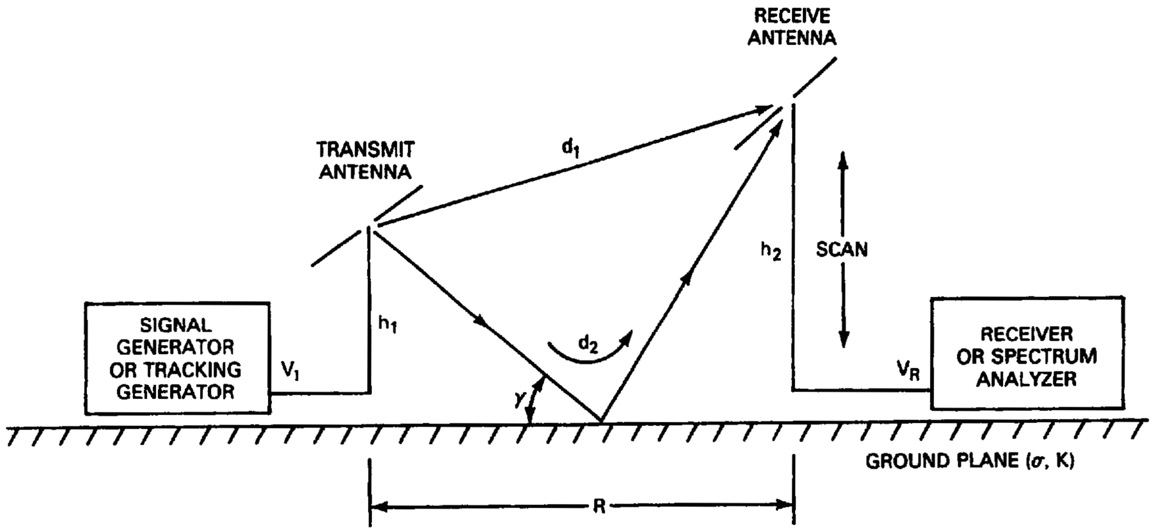


Figure A.1—Insertion loss measurement setup dipole and log-periodic antennas

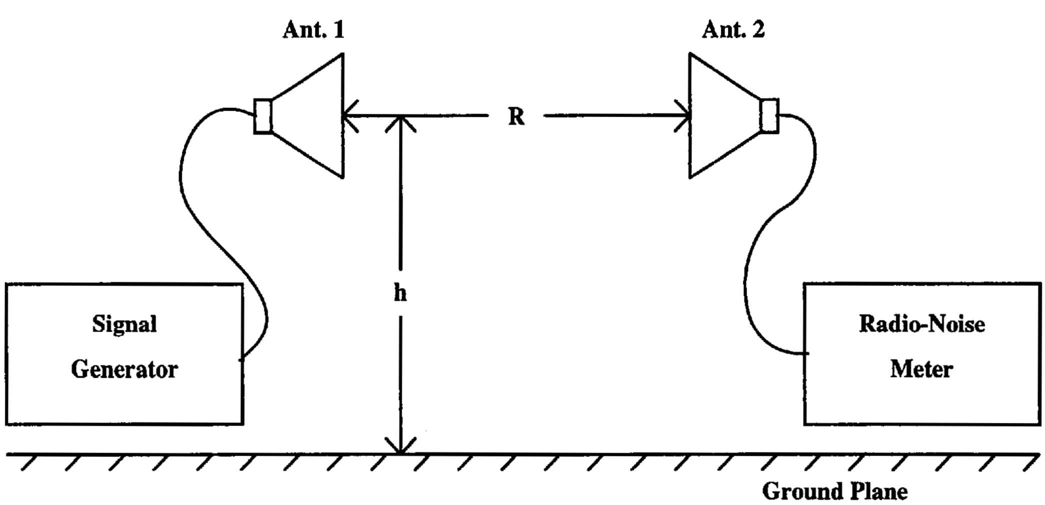


Figure A.2—Insertion loss measurement setup horn antennas

Annex B

(informative)

The discrete frequency method

The discrete frequency method may be performed using a worksheet approach. The simple worksheets (1) order the site attenuation measurements, and (2) direct the application of the simultaneous equations. Refer to Figure 2 for the measurement geometry.

Figures B.1 and B.3 contain the recommended worksheets for making the necessary measurements and calculations for determining the antenna factors. The worksheet in Figure B.1 is filled out for illustrative purposes for each pairing of antennas (Figure B.2). Then the data are extracted from these worksheets to fill out the worksheet in Figure B.3. The computations in this worksheet provide the antenna factors for each of the three antenna pairs. The following is an example for using the worksheets.

Three biconical dipole antennas are to be calibrated. For the purpose of the example, data are shown at only one frequency. The usual calibration would be carried out at the number of frequencies indicated in Table 1 (Table 2 for horn antennas at 1 GHz and higher). The results are shown in Figure B.4. (The antennas could have been any three different types in their suitable frequency range; e.g., a biconical dipole, a half wavelength resonant dipole, and a broadband dipole could have been used.)

Test Setup Data

Frequency (f_M)	30 MHz
Spacing (R)	10 m
Source Height (h_1)	2 m
Search Height (h_2)	1–4 m

Steps (Substitution Method):

1) The signal generator and measuring instrument are allowed to warm up and stabilize, and the substitution attenuators are inserted.
2) A site attenuation measurement including height search for maximum signal strength is made through the antennas, and the substitution attenuators are adjusted for a reference indication on the measuring instrument. These data are then recorded on the worksheet of Figure B.1.
3) The antenna cables (each containing an in-line attenuator) are disconnected from the antennas and connected directly together. The substitution attenuators are adjusted to give the same reference indication as in step 2), and the data are recorded on the worksheet.
4) The difference in attenuation is found by subtracting "attenuation for antenna-to-antenna mode" from the "attenuation for direct connection mode" and is recorded in the "difference" column on the worksheet.
5) Two more sets of measurements are then made, one for each of the remaining antenna pairings, and a Figure B.1 worksheet is filled out for each (see Figure B.2).
6) The numbers from the "difference" columns of each of the Figure B.1 worksheets are extracted and entered in the appropriate columns of the Figure B.3 worksheet (see Figure B.4), and the remaining steps indicated in the columns are performed to find the three antenna factors. The values of column E are obtained from Table 1 (Table 2 for horn antennas at 1 GHz and higher).

DATE: ____/____/____ PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RECEIVING ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB A_1, A_2, or A_3 (see equations (4), (5), and (6)]	ANTENNA PAIR:______________ ANTENNA 1: ANTENNA 2: ANTENNA 3: SEPARATION DISTANCE: TRANSMIT HEIGHT:
					NOTES:
					LIST EQUIPMENT SERIAL NUMBERS

Figure B.1—Data sheet for three-antenna method for insertion loss determination

DATE: ____/____/____ PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, A_1, A_2, or A_3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 1 - 2 ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	37.5	101.0	63.5	NOTES:

DATE: ____/____/____ PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, A_1, A_2, or A_3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 1 - 2 ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	37.1	101.3	64.2	NOTES:

DATE: ____/____/____ PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, A_1, A_2, or A_3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 2 - 3 ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	36.8	101.3	64.5	NOTES:

Figure B.2—Examples of use of data sheet for insertion loss determination

DATE:____/____/____ SEPARATION DISTANCE: ________

FREQ.	A	B	C	F	G	H	D	E	AF_1	AF_2	AF_3
MHz	Attn. Data Antenna Pair 1 – 2 A_1	Attn. Data Antenna Pair 1 – 3 A_2	Attn. Data Antenna Pair 2 - 3 A_3	A + B – C	A + C – B	B + C – A	10 log[F] – 24.46	E_D^{max}	$D + \frac{E+F}{2}$	$D + \frac{E+G}{2}$	$D + \frac{E+H}{2}$

Figure B.3—Three antenna method: Antenna factors computation chart

DATE:____/____/____

SEPARATION DISTANCE: *10 m*

FREQ.	A	B	C	F	G	H	D	E	AF_1	AF_2	AF_3
MHz	Attn. Data Antenna Pair 1 – 2 A_1	Attn. Data Antenna Pair 1 – 3 A_2	Attn. Data Antenna Pair 2 – 3 A_3	A + B – C	A + C – B	B + C – A	10 log[F] – 24.46	E_D^{max}	$D + \frac{E+F}{2}$	$D + \frac{E+G}{2}$	$D + \frac{E+H}{2}$
30	63.5	64.2	64.5	63.2	63.8	65.2	*–9.7*	*–22.3*	10.8	11.1	11.8

Figure B.4—Example of antenna factors computation chart use

Annex C

(informative)

The reference antenna

The reference antenna is a tuned, half-wavelength-resonant dipole with a series-parallel coaxial stub balun. Figure C.1(a) shows the balun structure in a pictorial way. The equivalent circuit, shown in Figure C.1(b), shows the impedances seen at the feedpoint to the balun. The shorted balanced line and the open coaxial sections appear in parallel and series with the load, respectively. The parallel section forces the load to be fed in a balanced manner. Although the use of a parallel shorted stub alone will affect a balanced to unbalanced transformation, it provides a useful match only over the narrow range where the stub presents a high impedance. The combined action of the series open stub and parallel shorted stub extends the range of approximate match. The two matching stubs are one-quarter of an electrical wavelength at the center of the frequency band in which the balun is intended to operate. At the center of this band, where both stubs are resonant, the series coaxial-line open stub looks like a short circuit, while the parallel balanced-line shorted stub looks like an open circuit. Equations for the stub impedance are

— For a series stub,

$$Z_s = jZ_o \cot \theta_s \tag{C.1}$$

— For a parallel stub,

$$Z_p = jZ_o \tan \theta_p \tag{C.2}$$

where

θ_s, θ_p are the electrical length of series and parallel stubs respectively, and

Z_o, Z_p are the coaxial and balanced line characteristic impedance, respectively.

Figure C.1 (c) shows how compensation occurs. Assume that the electrical angle is slightly above 90°, corresponding to a frequency slightly above stub resonance. The lag introduced by Z_s is nearly canceled by the lead produced by Z_p. At frequencies below resonance the roles of the stubs are reversed, as shown in Figure C.1 (c). It is shown in FCC Project 3235-33 [B5] that a nearly perfect match exists when Equation (C.3) is satisfied, and that a VSWR of under 1.5:1 can be expected over a frequency range of nearly 3:1.

$$\theta = \arcsin\, (Z_o/R_a)^{1/2} \tag{C.3}$$

where

Z_o is the characteristic impedance of the coaxial line, and

R_a is the radiation resistance of the resonant antenna.

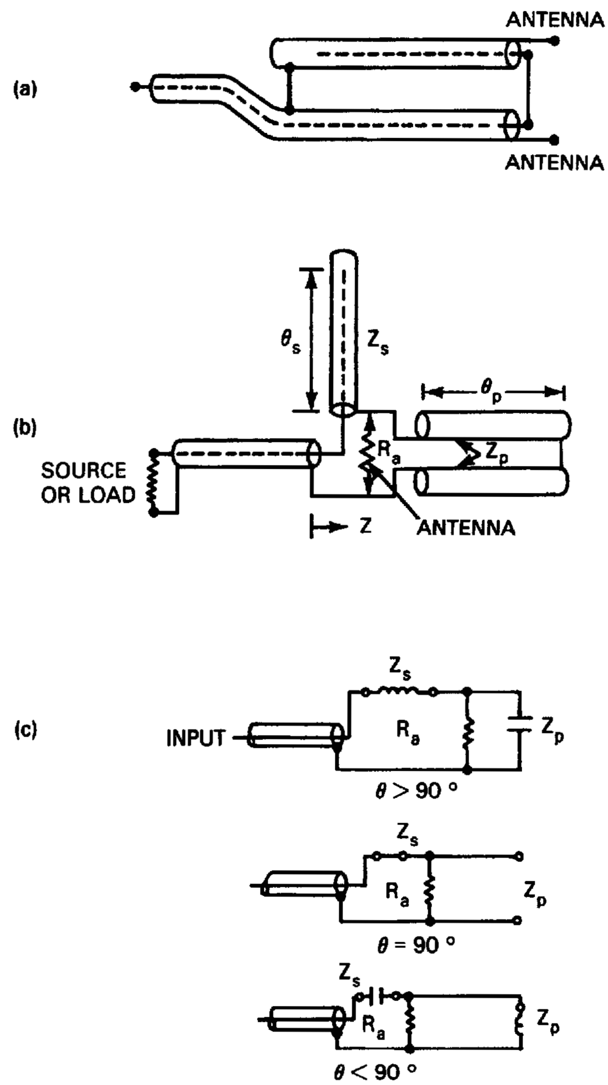


Figure C.1—Reference antenna balun construction, equivalent circuit, and explanation of compensation mechanism

Annex D

(informative)

Rod (Monopole) performance equations

The following equations may be used to determine the effective height and the self-capacitance of rod or monopole antennas of unusual dimensions. For these equations to hold, the rod shall be shorter than $\lambda/4$.

$$h_e = \frac{\lambda}{2\pi}\tan\frac{\pi h}{\lambda}, \text{ m} \tag{D.1}$$

$$C_a = \frac{55.6h}{\ln\frac{2h}{a} - 1} \, \frac{\tan\frac{2\pi h}{\lambda}}{\frac{2\pi h}{\lambda}}, \text{ pF} \tag{D.2}$$

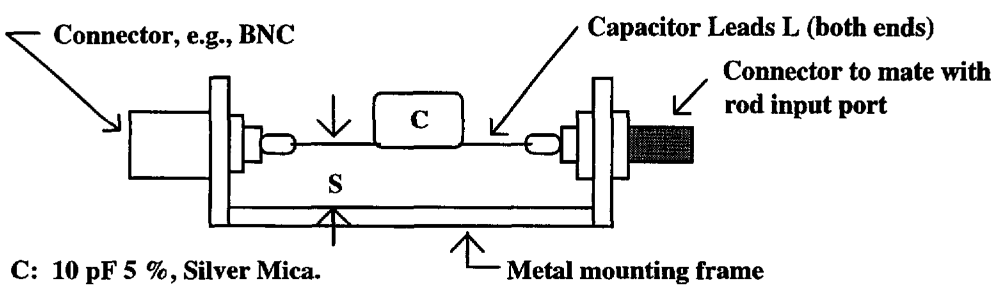
where:

h_e is the effective height of the antenna, m
h is the actual length of the rod element, m
a is the average radius of the rod element, m
λ is the wavelength, m

D.1 Dummy antenna considerations

The capacitor used as the equivalent capacitance in the dummy antenna should be mounted in a small metal box or on a small metal frame. The leads shall be kept as short as possible and kept close to the surface of the metal box or frame. A spacing of 5 mm to 10 mm is suggested. Figure D.1 shows an example.

The T-connector used in the antenna factor measurement setup may be built into the dummy antenna box. Also, a resistor network to provide matching to the generator and the RF voltmeter (receiver) may be built into the dummy antenna box.



C: 10 pF 5 %, Silver Mica.

S: Lead Spacing, 5 to 10 mm (10 mm from all surfaces if enclosed in box).

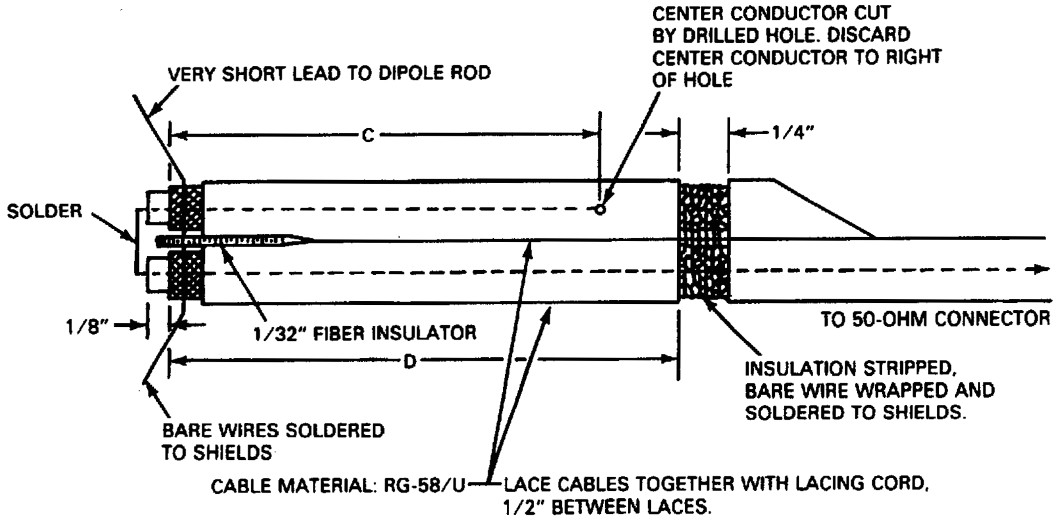
L: Lead length, as short as possible but not greater than 12 mm. (Total lead length not greater than 40 mm including both capacitor leads and length of rod port connector.)

Figure D.1—Example of mounting of capacitor in dummy antenna

Annex E

(informative)

Example drawings of reference antenna [B5]



FREQUENCY RANGE (MHz)	LENGTH C (in)	LENGTH D (in)
20-65	43.3	43.3
65-180	14.2	16.25
180-400	6.125	7.5
400-1000	2.7	3.0

Figure E.1—Reference antenna balun dimensions

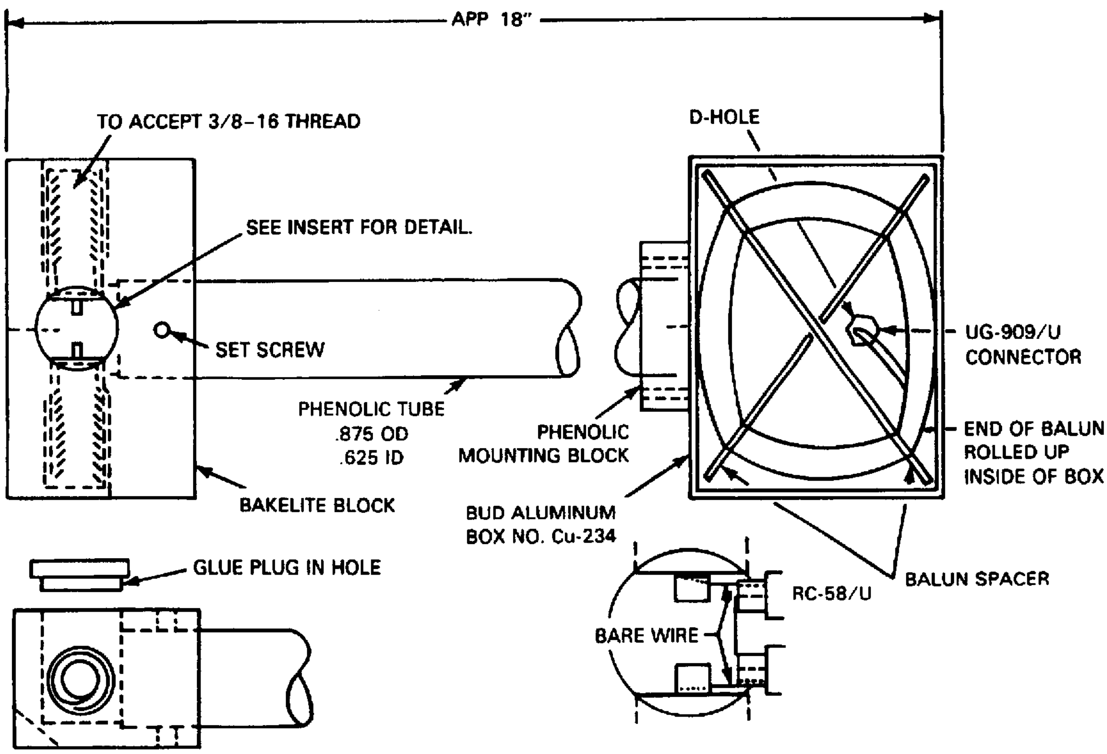


Figure E.2—20 MHz – 65 MHz reference dipole assembly

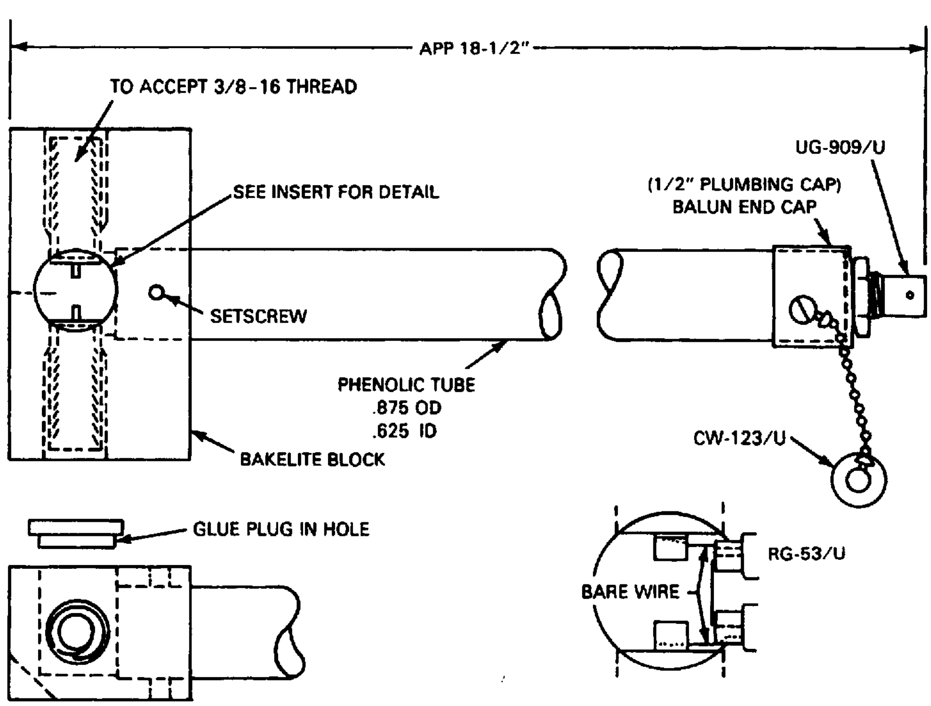


Figure E.3—65 MHz –180 MHz and 180 MHz – 400 MHz reference dipole assembly

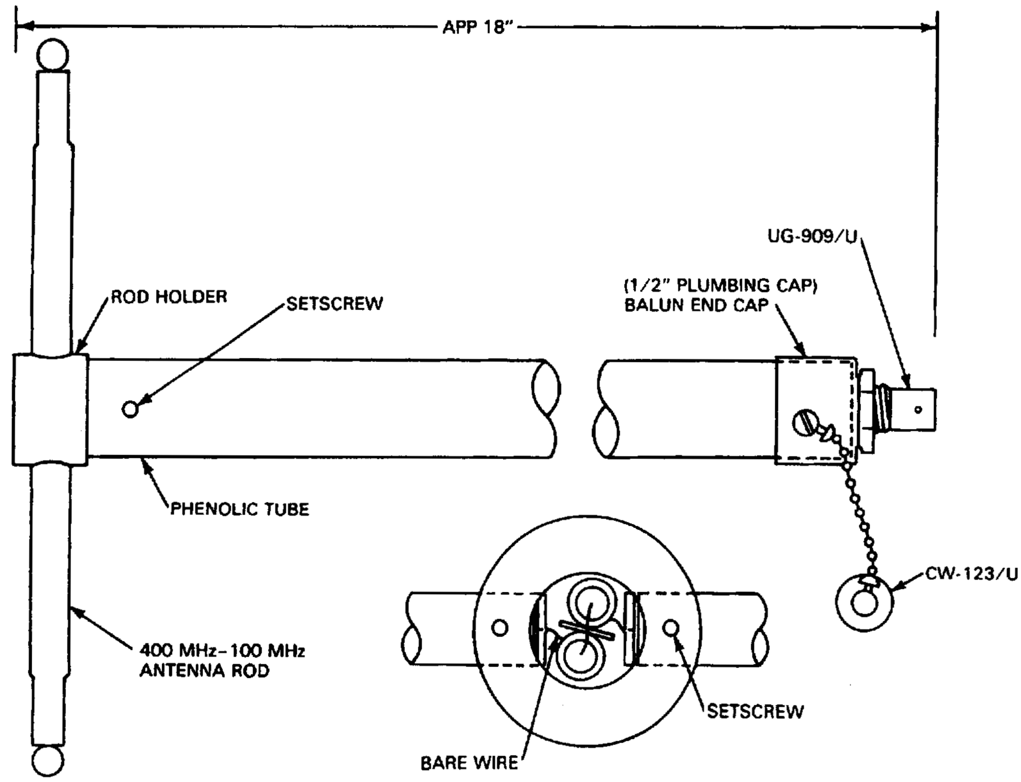


Figure E.4—400 MHz –1000 MHz reference dipole assembly

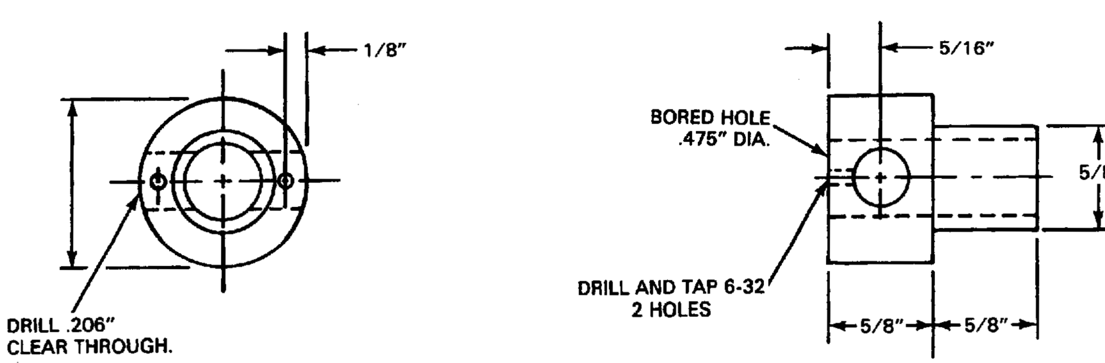
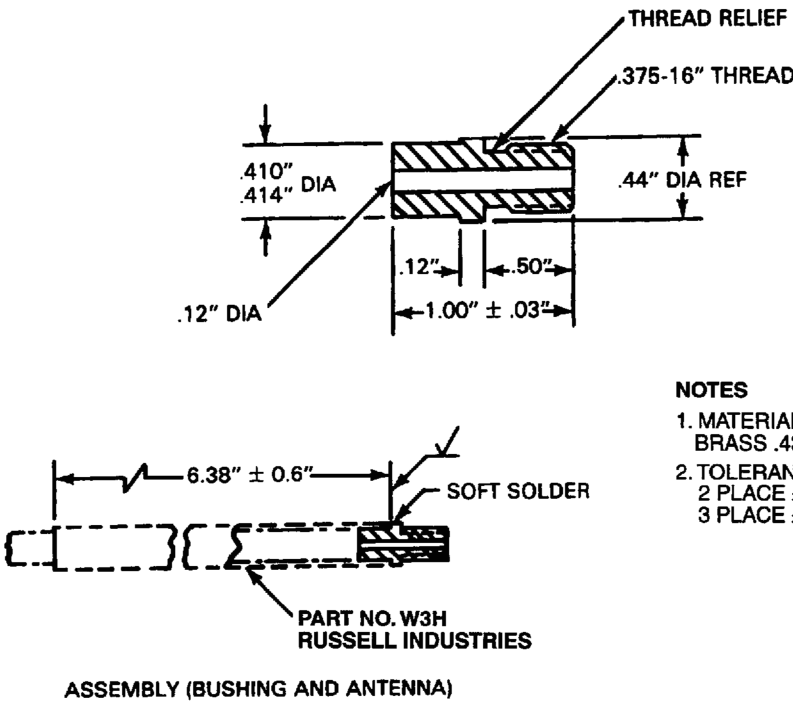
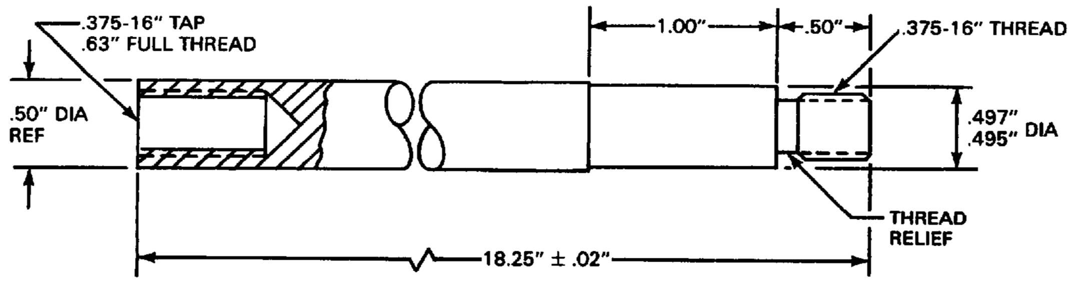


Figure E.5—Dipole rod holder, 400 MHz –1000 MHz



NOTES
1. MATERIAL: FREE MACHINING BRASS .437" DIA
2. TOLERANCES: EXCEPT AS NOTED
   2 PLACE ± .01"
   3 PLACE ± .005"

Figure E.6—Antenna rods, 65 MHz–180 MHz



NOTES
1. MATERIAL: .50" DIA. 6061-T6 AL.
2. POLISH SURFACE
3. TOLERANCES: EXCEPT AS NOTED
   2 PLACE ± .01"
   3 PLACE ± .005"

Figure E.7—Antenna rod extenders, 25 MHz–65 MHz

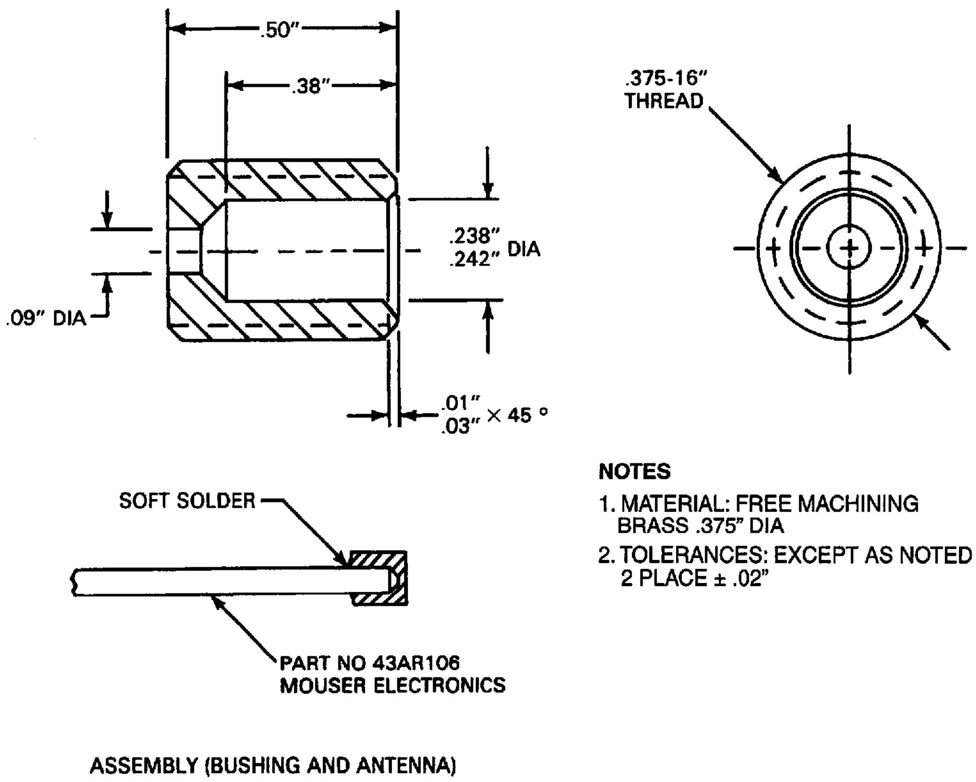


Figure E.8—Antenna rods, 180 MHz–400 MHz

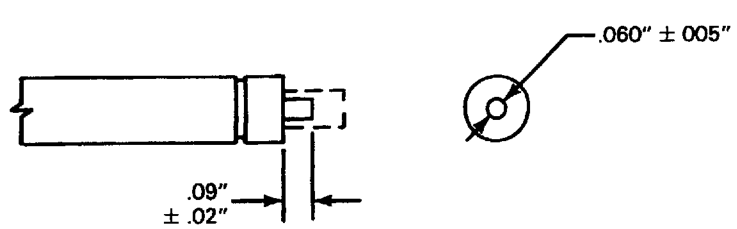
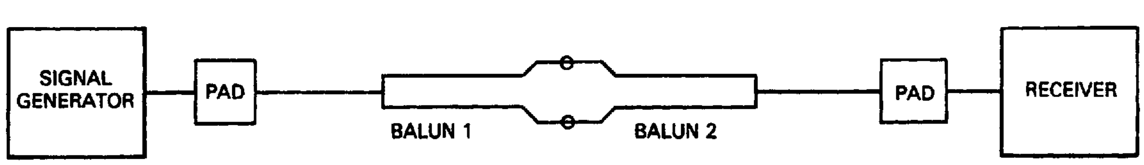


Figure E.9—Antenna rods, 400 MHz–1000 MHz



NOTE—All cabling and instrumentation are 50 Ω impedance. Use shortest possible connections between baluns.

Figure E.10—Preassembly balun loss check

Annex F

(informative)

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